Canadian Journal of Earth Sciences
Revue canadienne des sciences de la Terre

**Age and origin of the Cannon Point syenite, Essex County,
New York: Southernmost expression of Monteregian Hills
magmatism?**

Journal:	<i>Canadian Journal of Earth Sciences</i>
Manuscript ID	cjes-2016-0144.R1
Manuscript Type:	Article
Date Submitted by the Author:	31-Oct-2016
Complete List of Authors:	Bailey, David; Hamilton College, Geosciences Lupulescu, Marian; New York State Museum Chiarenzelli, Jeffrey; St Lawrence University, Geology Traylor, Jonathan; Hamilton College, Geosciences
Keyword:	Mesozoic, geochronology, geochemistry, igneous rocks, New York

**Age and origin of the Cannon Point syenite,
Essex County, New York:
Southernmost expression of Montereian Hills
magmatism?**

David G. Bailey

Geosciences Dept., Hamilton College, Clinton, NY

315-859-4142; dbailey@hamilton.edu

Marian Lupulescu

New York State Museum, Albany, NY

marian.lupulescu@nysed.gov

Jeffrey Chiarenzelli

St. Lawrence University, Canton, NY

jchiarenzelli@stlawu.edu

Jonathan P. Traylor

Hamilton College, Clinton, NY

jpspeeddemon@gmail.com

Abstract

Two syenite sills intrude the local Paleozoic strata of eastern New York State and are exposed along the western shore of Lake Champlain. The sills are fine-grained, alkali feldspar syenites and quartz syenites, with phenocrysts of sanidine and albite. The two sills are compositionally distinct, with crossing REE profiles and different incompatible element ratios, prohibiting a simple petrogenetic relationship. Zircon extracted from the upper sill yield a U-Pb age of 131.1 ± 1.7 Ma, making the sills the youngest known igneous rocks in New York State. This age is similar to the earliest intrusions in the Monteregian Hills of Quebec, over 100 km to the north. Sr and Nd radiogenic isotope ratios are also similar to those observed in some of the syenitic rocks of the eastern Monteregian Hills.

The Cannon Point syenites have compositions typical of A-type, within-plate granitoids. They exhibit unusually high Ta and Nb concentrations, resulting in distinct trace element signatures that are similar to silicic rocks of the Valles Caldera, a large, rift-related magmatic system. We suggest that the Cannon Point syenites were melts derived primarily by anatexis of old, primitive, lower crustal material in response to Mesozoic rifting and to the intrusion of mantle-derived magmas. The sills indicate that the effects of continental rifting were spatially and temporally extensive, resulting in the reactivation of basement faults in the Lake Champlain valley hundreds of kilometers west of the active rift boundary, and crustal melting over 50 Ma after the initiation of rifting.

Keywords: Mesozoic, Igneous Rocks, New York, Geochronology, Geochemistry

Introduction

Magmatic activity was compositionally diverse and geographically widespread across New England throughout the Mesozoic. Igneous rocks range in age from ~ 240 Ma to ~85 Ma (McHone and Butler 1984), and in composition from highly alkaline mafic intrusions (e.g. lamprophyres) to highly alkaline felsic intrusions (e.g. nepheline syenites and quartz syenites), to high silica granites (Eby 1985; MCHone 1987). MCHone and Butler (1984) identified and described four distinct igneous provinces in the region: 1) the Coastal New England Province, 2) the Eastern North America Dolerite Province, 3) the White Mountain Province, and 4) the New England – Quebec Province. Cannon Point lies on the western margin of all of this activity, within the broad New England – Quebec (NEQ) magmatic province (Figure 1). Magmatism in the western portion of the NEQ was dominated by mafic, alkaline intrusions, particularly in the Monteregian Hills region of southern Quebec (Eby 1987) and throughout the Lake Champlain valley (McHone 1987; MCHone and MCHone 1999). Silica-saturated magmas in this area are uncommon, unlike in the White Mountain province where they are dominant (Eby et al. 1992; Foland and Allen 1991). Other than the small ($< 0.2 \text{ km}^2$) Barber Hill syenitic stock ~5 km due east of Cannon Point in Charlotte, VT, the closest similar silicic intrusives are more than 100 km to the north at Mont Brome and Mont Shefford in the Monteregian Hills, or $> 150 \text{ km}$ to the east in the White Mountains of New Hampshire. Previously identified Mesozoic plutonic rocks in upstate New York are limited to small, but numerous kimberlitic dikes and diatremes (Bailey and Lupulescu 2015).

Mesozoic magmatism in the NEQ and in the WMMS provinces has been ascribed to two fundamentally different tectonic mechanisms: 1) asthenospheric mantle plume-derived melts related to the Great Meteor Hotspot (Crough 1981; Heaman and Kjarsgaard 2000), or 2)

lithospheric mantle derived melts generated in response to Mesozoic rifting and crustal thinning (McHone and Butler 1984; Parrish and Lavin 1982; Roulleau and Stevenson 2013). The purpose of this study is to provide additional constraints on the timing and nature of Mesozoic magmatism in northeastern North America by obtaining age and geochemical data for the poorly known intrusions at Cannon Point.

Previous Studies, Field Relations, and Petrography

The Cannon Point intrusions are exposed along the western shore of Lake Champlain in northern New York over a distance of ~ 1.5 km (Figure 1). The sills were first recognized and mapped by Buddington and Whitcomb (1941), but the only subsequent work done on these intrusions was by three Middlebury College students over 30 years ago (Beyer 1971; Conard 1983; Crocker 1971). While initially thought to be lava flows (Beyer, 1971), field relations clearly reveal that there are at least two sills that intrude the local dark gray, shaly limestones of the Middle Ordovician Trenton Group (Conard 1983) (Figure 2). Both sills exhibit ~25 cm thick chilled margins where in contact with the limestone, and the thickness of the limestone between the two sills varies from 2 to 50 cm. The two sills each have a minimum thickness of 5 m; there are no exposures that show a complete vertical section through either sill.

Both sills are porphyritic, with glomerocrysts of feldspar present in nearly all samples; this texture is best observed in the finer-grained chilled margins of the intrusions. The feldspar phenocrysts are sub- to euhedral, 1-5 mm in length, and comprise 2-25 modal percent of individual hand samples. Phenocrysts of both albite and sanidine are present, with sanidine comprising >90% of the phenocryst assemblage. The sanidine phenocrysts exhibit

simple Carlsbad twins (Figure 3), are microperthitic, have poorly developed Rapakivi texture, and are moderately to extensively altered, being replaced by sericite and calcite. SEM/EDS analysis of the phenocrysts reveals that they are fairly homogeneous, with compositions averaging $\sim \text{Or } 80 \pm 5$; albitic rims on the sanidine as well as the albite phenocrysts have compositions $\sim \text{Ab } 92 \pm 5$. No other phenocryst phases were observed, although sparse 0.5 - 1 mm long aggregates of secondary minerals (calcite, titanite, rutile, synchesite, and pyrite) exhibit shapes that suggest they may be pseudomorphs after amphibole.

Groundmass textures range from spherulitic, to trachytic, to hypidiomorphic granular, to granophyric – generally related to the distance from a chilled margin. Groundmass phases identified, in order of decreasing abundance, are alkali feldspar, albite, quartz, magnetite, and zircon. All of the rocks have been altered, some quite extensively. This is evidenced by the ubiquitous sericitization of the feldspars, and the carbonatization of many samples.

Methods

Thirteen hand samples were collected from exposures on the western shore of Lake Champlain just south of the town of Essex, NY. Two thin sections were prepared from each hand sample for petrographic and SEM/EDS analysis.

All thirteen samples were prepared for whole-rock geochemical analysis. The hand samples were crushed in a hardened steel jaw crusher, and then pulverized to a fine powder using a tungsten carbide ring mill. Rock powders were sent to the Geoanalytical Laboratory at Washington State University (WSU) for major and trace element analysis by X-Ray Fluorescence (XRF) spectrometry. The samples were analyzed on an automated Thermo-

ARL XRF spectrometer using 40 international standards for calibration. Splits of the rock powders were also sent to Washington State University for rare earth and additional trace element analyses by inductively coupled plasma mass spectrometry (ICP-MS). Detailed sample preparation protocols, analytical methods, and estimates of analytical precision and accuracy are available at <http://soe.wsu.edu/facilities/geolab/technotes/>.

Three whole-rock samples were selected for Sr and Nd isotope analyses at the Isotope Geology and Geochronology Research Facility at Carleton University, Ottawa, Ontario. Two of the least altered samples, one from each sill, along with one of the most altered samples (based upon petrographic and geochemical criteria discussed below) were selected for isotopic analysis. Detailed analytical methods are described in Cousens et al. (2008).

One large rock sample was sent to the Arizona Laserchron Center at the University of Arizona for radiometric dating. Over 100 zircons were extracted from the sample by traditional methods of crushing and grinding, followed by separation with a Wilfley table, heavy liquids, and a Frantz magnetic separator. Selected zircon grains were incorporated into a 1" diameter epoxy mount; the grains were ground to approximately half-thickness, polished, imaged with cathodoluminescence, and cleaned prior to isotopic analysis. U-Pb geochronology of the zircons was conducted by laser ablation multicollector inductively coupled plasma mass spectrometry (LA-MC-ICPMS). Detailed analytical methods and estimates of analytical precision and accuracy are provided in Gehrels et al. (2008) and in Appendix 1.

Results

Whole-Rock Geochemistry

On the basis of modal mineralogy, the coarser-grained samples have compositions that cluster around the quartz syenite field on the IUGS QAPF diagram. Because the majority of the samples are extremely fine-grained, it is easier to represent their compositions on the total alkali versus silica diagram (Figure 4), on which data from the Cannon Point sills plot in the trachyte and rhyolite compositional fields. The two sills are chemically distinct, with the lower sill having relatively lower silica and higher total alkali contents, as well as higher La/Sm and Ce/Ta ratios (Table 1; Figures 4 and 5). While the two sills have mineralogies and bulk compositions similar to some of the syenitic units in the White Mountains and in the Montereian Hills (Fig. 4), their trace element characteristics are distinct (Fig. 5).

Like most alkaline granitoids, both sills have relatively elevated REE concentrations and pronounced negative europium anomalies, probably reflecting fractionation of alkali feldspar (Leeman and Phelps 1981) (Fig. 6a). The higher silica and generally more evolved upper sill has a lower LREE concentration than the lower sill, more chemical variability, less steep LREE trends, a more pronounced negative europium anomaly, and a flatter overall REE profile.

Zircon Geochronology

Zircon is a minor groundmass phase in the coarser-grained sill interiors; it rarely exceeds 100 microns in length. Nine grains extracted from the upper sill were analyzed for trace element composition by LA-ICPMS at Rensselaer Polytechnic Institute. The zircons are uniform in composition, being strongly enriched in the HREE and having pronounced

positive cerium anomalies and only minor negative europium anomalies (Fig. 6b), typical of magmatic zircons from syenitic rocks (Belousova et al. 2002).

Twenty-nine zircon grains from the upper sill dated using LA-MC-ICPMS at the Arizona Laserchron Center yielded concordant U-Pb ages (Table 2). The weighted mean age of the data is 131 ± 1.7 Ma (MSWD = 0.36; Prob = 0.99) (Figure 7), which is interpreted as the time of emplacement and crystallization of the sill. This age is broadly consistent with the measured ages of other igneous rocks in the Montereian Hills province that range between 108 and 149 Ma (Figure 8), although some researchers have argued that most of the plutons in the Montereian Hills were intruded over a very short time interval of 123.5 ± 1 Ma (Eby 2006; Foland et al. 1986). Eby (1987) noted that rocks in the Montereian Hills fall into two groups: a younger and volumetrically dominant group of highly undersaturated rocks with ages between 118-122 Ma, and an older group with ages between 130-140 Ma which contains slightly undersaturated to silica-saturated rock compositions. The Cannon Point quartz syenites clearly fit into this older group. The nearby Barber Hill syenite in Vermont has, in the past, been associated with the Cannon Point syenite based upon their close proximity (McHone 1987), although their measured ages differ by 20 Ma (Figure 8). The age on the Barber Hill syenite of 111 ± 2 Ma (Armstrong and Stump 1971) is a K-Ar date on “slightly altered biotite” and, as pointed out by McHone (1987), is very likely too young due to either argon loss or being a cooling age.

Magmatism in the White Mountain Magma Series (WMMS) occurred over a wider time span, from ~ 200-100 Ma, but with two apparent episodes of increased activity: one at ~ 180 Ma, and the other at ~ 120 Ma (Foland and Faul 1977). Hubacher and Foland (1991) argued that the younger WMMS intrusions of northern New England intruded over a very short time

interval of 122.5 $\pm$ 1 Ma, essentially synchronous with the main episode of magmatism in the Montereian Hills. The main difference between Montereian Hills magmatism and the younger White Mountain magmatism is the predominance of undersaturated rocks in the Montereian Hills province, and of silica-saturated rocks in the younger WMMS province (Eby 1987). The Cannon point syenites clearly are part of the widespread episode of early Cretaceous magmatism in the New England – Quebec province with similarities to syenitic units in both the Montereian Hills and in the younger WMMS. They are, however, spatially removed from the main areas of magmatic activity, and are some of the older syenitic rocks of the early Cretaceous episode of igneous activity in the region.

Radiogenic Isotope Ratios

Three whole-rock samples were selected for Sr and Nd isotope analysis; one from each of the two sills, and the third from one of the most extensively altered samples in order to evaluate the effects of the metasomatic alteration on the two isotope systems. Because sericitization and carbonatization were the two visually observed styles of alteration, and the secondary phases produced are volatile-bearing, we used the loss on ignition as a proxy for the degree of alteration. The most apparent chemical effect of alteration is an increase in the amount of calcium, which is positively correlated with the loss on ignition values (Figure 9a). Not surprisingly, Sr concentrations also appear to have been affected by the alteration processes (Figure 9b). Two samples with the lowest LOI and CaO concentrations, one from each sill, were selected for isotopic analysis. Additionally, the most altered sample was also analyzed in order to provide information on the effects of alteration on the two isotopic systems. All three samples yielded unusual and nearly identical isotopic ratios, with

relatively high $^{87}\text{Sr}/^{86}\text{Sr}_i$ (Figure 10). Some syenitic rocks from the eastern Montereian complexes (i.e. Mt. Brome and Shefford) have similar isotopic compositions, which Landoll and Foland (1996) interpreted as being the result of assimilation-fractional crystallization processes. However, because of the low (36-200 ppm) Sr concentrations in the Cannon Point samples, and because all of the samples have clearly experienced hydrothermal alteration, we interpret the data to indicate a complete resetting of the Sr isotope ratios, probably reflecting input of Sr from the surrounding Ordovician limestones.

Discussion

Mesozoic magmatism in northeastern North America began at approximately 200 Ma with voluminous flood basalt volcanism related to continental rifting and the opening of the Atlantic (McHone 2012; McHone et al. 2014; Schlische et al. 2003). Post-Circum-Atlantic Magmatic Province (CAMP) activity was widely distributed, both geographically and temporally, and was compositionally diverse. Two areas of concentrated igneous activity were in the White Mountains of central and northern New Hampshire, and in the Montereian Hills of southern Quebec. In the White Mountains, there were two pronounced periods of activity (one ~ 180 Ma and a second ~ 125 Ma) that generated large volumes of predominantly silica-saturated melts (e.g. diorites, granites, and syenites). In the Montereian Hills, most of the igneous activity was ~ 125 Ma, and was dominated by silica-undersaturated melts (e.g. ijolites, essexites, nepheline diorites, etc.). The localized, and relatively linear distribution of intrusions in both of these areas has been explained by the movement of the North American plate over a mantle hotspot (Crough 1981; Foland et al. 1986), or alternatively, by localization of magmas along ancient faults in the basement that

were reactivated by Mesozoic rifting (McHone and Butler 1984; Roulleau and Stevenson 2013). Outside of these two areas, Mesozoic igneous activity was limited, represented primarily by small mafic alkaline dikes (McHone 1987) or small kimberlitic intrusions (Bailey and Lupulescu 2015). The two sills at Cannon Point are exceptions to this pattern, being relatively large syenite intrusions over 100 km south of the Montereian Hills, and 150 km west of the WMMS. With an age of 131 Ma, they are also some of the oldest Cretaceous intrusions in the region.

The two sills have distinct chemical compositions, with the upper sill being more evolved relative to the lower sill (Figures 4-6). The dramatically different REE and incompatible element ratios in the two sills prohibit the upper sill from being derived by any simple fractionation process from the lower sill; the data are more consistent with an origin of each sill by different degrees of partial melting of a primitive, lower crustal source. The lack of any contemporaneous mafic magmas, along with the apparently modified radiogenic isotope ratios, make it difficult to construct a more detailed petrogenetic model for these syenites.

The Cannon Point syenites have bulk compositions and trace element concentrations typical of within-plate granitoids, and are similar to silicic rocks in the Montereian Hills and the White Mountains (Figure 11). Their trace element profiles are distinct from granitoids from hot spot or subduction-related tectonic settings (e.g. lower Ba/Th and higher Nb/Ce ratios) (Figure 12a) but are, not surprisingly, similar to the trace element profiles of silicic rocks from the Montereian Hills and the White Mountains (Figure 12b). One of the most notable features of these rocks is their unusually high Ta and Nb contents, which results in unusually low Ba/Ta ratios, and correspondingly high Nb/Y ratios (Figure 12b). The only other silicic igneous rocks that we have found with similar trace element characteristics are

the tuffs and rhyolites from the Valles Caldera in New Mexico, which have been interpreted as melts of hybridized Precambrian crust generated within an incipient continental rift (Rowe et al. 2007). The occurrence of silicic igneous rocks with similar chemical characteristics within the Lake Champlain valley, which has been interpreted as part of a failed ancient continental rift (Burke 1977; McHone 1987), supports the interpretation that the Cannon Point magmas formed by partial melting of Precambrian basement rocks, and that these magmas then intruded along ancient faults reactivated by Mesozoic rifting.

Conclusions

With an emplacement age of $\sim 131 \pm 1.7$ Ma, the syenitic intrusions at Cannon Point on the western shore of Lake Champlain are the youngest known igneous rocks in New York State. They are broadly similar in both age and chemical composition to intrusive rocks in the White Mountains of New Hampshire and the Monteregian Hills of Quebec, but they are over 100 km distant from either igneous province. We suggest that the Cannon Point magmas were generated in response to Mesozoic rifting and to the crustal intrusion of mantle-derived, alkaline magmas. The sills indicate that the effects of continental rifting were spatially and temporally extensive, resulting in the reactivation of basement faults in the Lake Champlain valley hundreds of kilometers west of the active rift boundary, and crustal melting over 50 Ma after the initiation of rifting.

Acknowledgements

The authors wish to thank the following people for their assistance on this project: Dave Tewksbury for preparing the regional map; Ken Bart for help with SEM/EDS mineral

analysis; Rick Conrey for XRF data and for reviewing an early draft of the manuscript; Jared Singer for help with LA-ICPMS zircon analysis; and Mark Pecha for assistance with U/Pb zircon analysis. John Aleinikoff and Robert Darling are thanked for providing constructive reviews of the manuscript.

Draft

References

- Armstrong, R., and Stump, E. 1971. Additional K-Ar dates, White Mountain Magma Series, New England. *American Journal of Science* **270**: 331-333.
- Bailey, D.G., and Lupulescu, M.V. 2015. Spatial, temporal, mineralogical, and compositional variations in Mesozoic kimberlitic magmatism in New York State. *Lithos* **212-215**: 298-310.
- Belousova, E.A., Griffen, W.L., O'Reilly, S.Y., and Fisher, N.I. 2002. Igneous zircon: trace element composition as an indicator of source rock type. *Contributions to Mineralogy and Petrology* **143**: 602-622.
- Beyer, B.J. 1971. A study of the intrusion at Barber Hill, Vermont and related volcanics at Cannon Point, New York. Middlebury College, Middlebury, Vermont.
- Buddington, A.F., and Whitcomb, L. 1941. Geology of the Willsboro Quadrangle, New York. New York State Museum Bulletin.
- Burke, K. 1977. Are lakes George and Champlain in Neogene graben reactivating early Paleozoic rifts? *Abstracts with Programs - Geological Society of America* **9(3)**: 247-248.
- Conard, P.H. 1983. Geochemistry and petrology of alkaline rocks at Cannon Point, NY and Barber Hill, VT. *In* *Geology*, Middlebury College. p. 46.
- Cousens, B.L., Prytulak, J., Henry, C.D., Alcazar, A., and Brownrigg, T. 2008. The geology, geochronology, and geochemistry of the Miocene - Pliocene ancestral Cascades arc, northern Sierra Nevada, California and Nevada: The roles of the upper mantle, subducting slab, and the Sierra Nevada lithosphere. *Geosphere* **4**: 829-853.
- Crocker, D.E. 1971. A short study of the igneous complexes at Barber Hill, Vermont and Cannon Point, New York. Middlebury College, Middlebury, VT.

- Crough, S.T. 1981. Mesozoic hot spot epeirogeny in eastern North America. *Geology* **9**: 2-6.
- Eby, G.N. 1985. Age relations, chemistry, and petrogenesis of mafic alkaline dikes from the Montereian Hills and younger White Mountain igneous provinces. *Canadian Journal of Earth Sciences = Revue Canadienne des Sciences de la Terre* **22**(8): 1103-1111.
- Eby, G.N. 1987. The Montereian Hills and White Mountain alkaline igneous provinces, eastern North America. *Geological Society Special Publications* **30**: 433-447.
- Eby, G.N. 2006. Carbonatites to alkali granites; petrogenetic insights from the Chilwa and Montereian Hills-White Mountain igneous provinces. Abstract Volume [Geological Association of Canada] **31**: 45-45.
- Eby, G.N., Krueger, H.W., and Creasy, J.W. 1992. Geology, geochronology, and geochemistry of the White Mountain Batholith, New Hampshire. Special Paper - Geological Society of America **268**: 379-397.
- Foland, K.A., and Allen, J.C. 1991. Magma sources for Mesozoic anorogenic granites of the White Mountain magma series, New England, USA. *Contributions to Mineralogy and Petrology* **109**(2): 195-211.
- Foland, K.A., and Faul, H. 1977. Ages of the White Mountain intrusives; New Hampshire, Vermont, and Maine, USA. *American Journal of Science* **277**(7): 888-904.
- Foland, K.A., Gilbert, L.A., Sebring, C.A., and Chen, J.-F. 1986. (super 40) Ar/ (super 39) Ar ages for plutons of the Montereian Hills, Quebec; evidence for a single episode of Cretaceous magmatism. *Geological Society of America Bulletin* **97**(8): 966-974.
- Gehrels, G.E., Valencia, V., and Ruiz, J. 2008. Enhanced precision, accuracy, efficiency, and spatial resolution of U-Pb ages by laser ablation-ultracollector-inductively coupled plasma-

- mass spectrometry. *Geochemistry, Geophysics, Geosystems* **9**. doi: 10.1029/2007GC001805.
- Heaman, L.M., and Kjarsgaard, B.A. 2000. Timing of eastern North American kimberlite magmatism; continental extension of the Great Meteor Hotspot track? *Earth and Planetary Science Letters* **178**(3-4): 253-268.
- Hubacher, F.A., and Foland, K.A. 1991. (super 40) Ar/ (super 39) Ar ages for Cretaceous intrusions of the White Mountain magma series, northern New England, and their tectonic implications. *Abstracts with Programs - Geological Society of America* **23**(1): 47-47.
- Landoll, J.D., and Foland, K.A. 1996. The formation of quartz syenite by crustal contamination at Mont Shefford and other Monteregian complexes, Quebec. *Canadian Mineralogist* **34, Part 2**: 301-324.
- Le Bas, M.J., and Streckeisen, A.L. 1991. The IUGS systematics of igneous rocks. *Journal of the Geological Society of London* **148, Part 5**: 825-833.
- Leeman, W.P., and Phelps, D.W. 1981. Partitioning of rare earths and other trace elements between sanidine and coexisting volcanic glass. *Journal of Geophysical Research* **86**.
- Ludwig, K.R. 2008. Isoplot. *Berkeley Geochronology Center Special Publication* **4**: 77.
- McHone, J.G. 1987. Cretaceous intrusions and rift features in the Champlain Valley of Vermont. *Norwich Univ., Dep. Earth Sci. : Northfield, VT, United States, United States*. pp. 237-253.
- McHone, J.G. 2012. Composition and age groups of the Central Atlantic magmatic province relative to the Tr-J extinction event. *Abstracts with Programs - Geological Society of America* **44**(2): 55-55.

- McHone, J.G., and Butler, J.R. 1984. Mesozoic igneous provinces of New England and the opening of the North Atlantic Ocean. *Geological Society of America Bulletin* **95**(7): 757-765.
- McHone, J.G., Hussey, A.M., II, West, D.P., Jr., and Bailey, D.G. 2014. The Christmas Cove Dike of coastal Maine, USA, and regional sources for early Mesozoic flood basalts in northeastern North America. *Atlantic Geology* **50**: 66-90. doi: 10.4138/atlgol.2014.004.
- McHone, J.G., and McHone, N.W. 1999. The New England-Quebec igneous province in western Vermont. *Annual Meeting - New England Intercollegiate Geological Conference* **91**: 341-358.
- Parrish, J.B., and Lavin, P.M. 1982. Tectonic model for kimberlite emplacement in the Appalachian Plateau of Pennsylvania. *Geology [Boulder]* **10**(7): 344-347.
- Pearce, J.A., Harris, N.B.W., and Tindle, A.G. 1984. Trace element discrimination diagrams for the tectonic interpretation of granitic rocks. *Journal of Petrology* **25**(4): 956-983.
- Rouleau, E., and Stevenson, R.K. 2013. Geochemical and isotopic (Nd–Sr–Hf–Pb) evidence for a lithospheric mantle source in the formation of the alkaline Monteregian Province (Quebec). *Canadian Journal of Earth Sciences = Revue Canadienne des Sciences de la Terre* **50**: 650-666.
- Rowe, M.C., Wolff, J.A., Gardner, J.N., Ramos, F.C., Teasdale, R., and Heikoop, C.E. 2007. Development of a continental volcanic field; petrogenesis of pre-caldera intermediate and silicic rocks and origin of the Bandelier magmas, Jemez Mountains (New Mexico, USA). *Journal of Petrology* **48**(11): 2063-2091. doi: 10.1093/petrology/egm050.

Schlische, R.W., Withjack, M.O., and Olson, P.E. 2003. Relative timing of CAMP, rifting, continental breakup, and basin inversion; tectonic significance. *Geophysical Monograph* **136**: 33-59.

Sun, S., and McDonough, W.F. 1989. Chemical and isotopic systematics of ocean basalts: implications for mantle compositions and processes. *In* *Magmatism in the Ocean Basins*. Edited by A.D. Saunders and M.J. Norry. Geological Society, London. pp. 313-345.

Draft

Figure Captions

Figure 1. Location of Cannon Point syenite relative to regional distribution of Mesozoic igneous rocks in eastern New York, southern Quebec and northern Vermont and New Hampshire. Boundaries of the New England – Quebec and White Mountain Magma Series provinces from McHone & Butler (1984). Hillshade base map derived from shuttle radar topography mission (SRTM) data available at <http://earthexplorer.usgs.gov>.

Figure 2. Field exposure at Cannon Point showing the chilled contacts of the two sills. Sills are separated by an ~ 50 cm thick layer of shaly limestone. Total height of exposure in photo ~ 5 m; hammer length = 28 cm.

Figure 3. Photomicrograph of sill margin showing sanidine phenocrysts with Carlsbad twinning set in a fine-grained, trachytic groundmass (sample CP-9A; XPL).

Figure 4. Total alkalis vs. silica diagram (after Le Bas and Streckeisen (1991)) showing the compositions of the upper and lower sills at Cannon Point. White Mountain Magma Series compositions (Eby et al. 1992) and high silica rocks from the Montereian Hills (Landoll & Foland 1996) are shown for comparison.

Figure 5. La/Sm and Ce/Ta ratios in granitoid rocks from Cannon Point, Montereian Hills, and the White Mountain Magma Series.

Figure 6. Chondrite-normalized REE concentrations in: a) whole-rock samples from the upper and lower sills at Cannon Point, and b) average values for each sill and for zircons extracted from the upper sill. Normalizing factors from Sun and McDonough (1989).

Figure 7. Weighted mean plot of concordant U-Pb zircon ages for the upper sill at Cannon Point.

Figure 8. Age of Cannon Point syenite shown on a histogram of ages of Monteregian Hills intrusives (from data compiled and available at Système d'information géominière of Québec website: http://sigeom.mines.gouv.qc.ca/signet/classes/I1108_afchCarteIntr?l=a). Age of Barber Hill syenite from Armstrong & Stump (1971). Ages are from many different analytical techniques over a period of many decades but still serve to illustrate the general pattern of Mesozoic igneous activity in the region.

Figure 9. Effects of alteration on the composition of the Cannon Point syenites: a) LOI versus CaO concentrations in the two sills showing strong positive correlation reflecting the extent of carbonatization of the samples; b) Sr vs CaO showing that Sr concentrations, and presumably Sr isotopic ratios, are also modified by carbonatization.

Figure 10. Initial Nd and Sr isotopic ratios of the Cannon Point sills compared to those of other Mesozoic granitoid intrusions from the WMMS (Foland and Allen 1991) and the Monteregian Hills (Landoll and Foland 1996). Epsilon Sr and Nd values are relative to present day bulk Earth values.

Figure 11. Trace element tectonic discrimination diagram for granitoid rocks (after Pearce et al. (1984)). Monterey Hills data from Landoll and Foland (1996); WMMS data from Eby et al. (1992).

Figure 12. Ocean ridge granite (ORG) normalized element abundance diagrams showing the relative concentrations of incompatible elements in the Cannon Point syenite relative to the concentrations in other high silica igneous rocks: a) Cannon Point syenite trace element profiles compared to silicic igneous rocks from subduction zone settings (Crater Lake and Tuolumne) and continental and oceanic hot spots (Yellowstone and Iceland); b) Cannon Point syenite trace element profiles compared to those of high silica rocks from the White Mountains, the Monterey Hills, and Valles Caldera. ORG normalizing values from Pearce et al. (1984); Monterey Hills nordmarkite data from Eby 1985); all other rock suite data downloaded from www.earthchem.org, filtered for igneous rocks with SiO₂ concentrations between 65 and 75 wt. percent.

Appendix 1:

Detailed methods for U-Pb geochronologic analyses of igneous zircon (Nu HR ICPMS)

U-Pb geochronology of zircons was conducted by laser ablation multicollector inductively coupled plasma mass spectrometry (LA-MC-ICPMS) at the Arizona LaserChron Center following their standard procedure (outlined below, and in Gehrels et al. (2008)).

Zircon crystals were extracted from samples by traditional methods of crushing and grinding, followed by separation with a Wilfley table, heavy liquids, and a Frantz magnetic separator. Samples were processed such that all zircons were retained in the final heavy mineral fraction. A split of these grains (generally 50-100 grains) were handpicked with the use of a binocular microscope and were not sieved prior to picking. The grains ranged in size from 50-200 microns; most were anhedral fragments. The selected grains were incorporated into a 1" epoxy mount together with fragments of the LaserChron center's Sri Lanka standard zircon. The mounts were sanded down to a depth of ~20 microns, polished, imaged using the cathodoluminescence mode of a scanning electron microscope, and cleaned prior to isotopic analysis.

The analyses involved ablation of zircon with a Photon Machines Analyte G2 Excimer laser using a spot diameter of 30 microns. The ablation pit was ~15 microns in depth. The ablated material was carried in helium into the plasma source of a Nu HR ICPMS, which is equipped with a flight tube of sufficient width that U, Th, and Pb isotopes are measured simultaneously. All measurements were made in static mode, using Faraday detectors with 3×10^{11} ohm resistors for ^{238}U , ^{232}Th , ^{208}Pb - ^{206}Pb , and discrete dynode ion counters for ^{204}Pb and ^{202}Hg . Ion yields were ~0.8 mv per ppm. Each analysis consisted of one 15-second

integration on peaks with the laser off (for backgrounds), 15 one-second integrations with the laser firing, and a 30 second delay to purge the previous sample and prepare for the next analysis.

For each analysis, the errors in determining $^{206}\text{Pb}/^{238}\text{U}$ and $^{206}\text{Pb}/^{204}\text{Pb}$ result in a measurement error of $\sim 1\text{-}2\%$ (at 2-sigma level) in the $^{206}\text{Pb}/^{238}\text{U}$ age. The errors in measurement of $^{207}\text{Pb}/^{206}\text{Pb}$ and $^{206}\text{Pb}/^{204}\text{Pb}$ also result in $\sim 1\text{-}2\%$ (at 2-sigma level) uncertainty in age for grains that are >1.0 Ga, but are substantially larger for younger grains due to low intensity of the ^{207}Pb signal. For most analyses, the cross-over in precision of $^{206}\text{Pb}/^{238}\text{U}$ and $^{207}\text{Pb}/^{206}\text{Pb}$ ages occurs at ~ 1.0 Ga.

^{204}Hg interference with ^{204}Pb is accounted for measurement of ^{202}Hg during laser ablation and subtraction of ^{204}Hg according to the natural $^{202}\text{Hg}/^{204}\text{Hg}$ of 4.35. This Hg correction is not significant for most analyses because our Hg backgrounds are low (generally ~ 150 cps at mass 204).

Common Pb correction is accomplished by using the Hg-corrected ^{204}Pb and assuming an initial Pb composition from Stacey and Kramers (1975). Uncertainties of 1.5 for $^{206}\text{Pb}/^{204}\text{Pb}$ and 0.3 for $^{207}\text{Pb}/^{204}\text{Pb}$ are applied to these compositional values based on the variation in Pb isotopic composition in modern crystalline rocks.

Inter-element fractionation of Pb/U is generally $\sim 5\%$, whereas apparent fractionation of Pb isotopes is generally $<0.2\%$. In-run analysis of fragments of a large zircon crystal (generally every fifth measurement) with known age of 563.5 ± 3.2 Ma (2-sigma error) is used to correct for this fractionation. The uncertainty resulting from the calibration correction is generally 1-2% (2-sigma) for both $^{206}\text{Pb}/^{207}\text{Pb}$ and $^{206}\text{Pb}/^{238}\text{U}$ ages. A comprehensive

review of uncertainty in LA-ICP-MS U-(Th-)Pb geochronology is available in Horstwood et al. (2016).

Concentrations of U and Th are calibrated relative to the LaserChron center's Sri Lanka zircon, which contains ~518 ppm of U and 68 ppm Th, and are accurate to ~20%. Uncertainties reported are at the 1-sigma level, and include only measurement errors. Analyses that are >20% discordant (by comparison of $^{206}\text{Pb}/^{238}\text{U}$ and $^{207}\text{Pb}/^{206}\text{Pb}$ ages) or >5% reverse discordant are discarded. The resulting interpreted ages are shown on Pb*/U concordia diagrams and weighted mean diagrams using the routines in Isoplot (Ludwig 2008). The weighted mean diagrams show the weighted mean (weighting according to the square of the internal uncertainties), the uncertainty of the weighted mean, the external (systematic) uncertainty that corresponds to the ages used, the final uncertainty of the age (determined by quadratic addition of the weighted mean and external uncertainties), and the MSWD of the data set.

References

- Gehrels, G.E., Valencia, V., and Ruiz, J. 2008. Enhanced precision, accuracy, efficiency, and spatial resolution of U-Pb ages by laser ablation-multicollector-inductively coupled plasma-mass spectrometry. *Geochemistry, Geophysics, Geosystems* **9**, doi: 10.1029/2007GC001805.
- Horstwood, M.S.A., Košler, J., Gehrels, G., Jackson, S.E., McLean, N.M., Paton, C., Pearson, N.J., Sircombe, K., Sylvester, P., Vermeesch, P., Bowring, J.F., Condon, D.J., and Schoene, B. 2016. Community-Derived Standards for LA-ICP-MS U-(Th-)Pb Geochronology – Uncertainty Propagation, Age Interpretation and Data Reporting.

Geostandards and Geoanalytical Research, **40**(3): 311-332. doi: 10.1111/j.1751-908X.2016.00379.x.

Ludwig, K.R. 2008. Isoplot. Berkeley Geochronology Center Special Publication **4**: 77.

Stacey, J.S., and Kramers, J.D. 1975. Approximation of terrestrial lead isotope evolution by a two-stage model. Earth and Planetary Science Letters **26**: 207-221.

Draft

Sample	CP-1A	CP-1B	CP-1D	CP-1E	CP-2	CP-3	CP-4	CP-5	CP-6	CP-7	CP-8	CP-9A	CP-9B
Sill	Lower	Lower	Upper	Upper	Lower	Lower	Lower	Upper	Upper	Upper	Upper	Lower	Lower
Latitude	44.28793	44.28793	44.28793	44.28793	44.28768	44.28697	44.28672	44.28636	44.28942	44.29001	44.29097	44.29116	44.29116
Longitude	-73.34560	-73.34560	-73.34560	-73.34560	-73.34570	-73.34600	-73.34600	-73.34637	-73.34529	-73.34641	-73.34732	-73.34748	-73.34748
XRF Major Elements (Weight %):													
SiO ₂	70.70	67.94	69.50	72.93	69.56	61.51	68.91	74.22	74.35	68.50	74.32	69.23	63.38
TiO ₂	0.23	0.21	0.07	0.13	0.24	0.18	0.23	0.07	0.10	0.06	0.07	0.23	0.19
Al ₂ O ₃	15.82	14.92	12.19	13.40	15.85	13.51	15.62	13.12	13.25	10.99	12.86	15.36	14.45
FeO*	1.66	1.61	1.14	1.41	1.74	1.34	1.47	1.15	1.19	1.15	1.12	1.43	1.61
MnO	0.20	0.24	0.27	0.27	0.22	0.20	0.18	0.25	0.22	0.23	0.27	0.19	0.22
MgO	0.02	0.13	0.15	0.07	0.01	0.45	0.10	0.07	0.02	0.26	0.03	0.08	0.18
CaO	0.09	1.63	3.51	0.14	0.06	6.53	0.46	0.12	0.04	4.75	0.18	0.34	4.61
Na ₂ O	5.76	5.84	4.76	4.76	6.36	5.12	5.59	5.03	4.96	3.58	5.18	5.45	5.69
K ₂ O	5.29	4.59	3.54	4.74	4.45	4.26	5.18	3.42	4.14	4.19	3.73	5.31	4.01
P ₂ O ₅	0.03	0.02	0.02	0.04	0.04	0.02	0.04	0.02	0.03	0.02	0.01	0.03	0.03
Sum	99.80	97.12	95.14	97.90	98.53	93.12	97.78	97.46	98.29	93.73	97.77	97.64	94.38
LOI	0.65	2.14	3.22	0.98	0.83	6.55	0.95	0.90	0.63	4.65	0.87	1.29	4.52
XRF Trace Elements (ppm):													
Ni	16	3	3	3	2	3	0	2	1	1	0	4	3
Cr	8	3	2	6	1	1	0	2	3	1	2	1	3
Sc	4	3	2	2	3	3	3	1	2	2	1	2	3
V	3	6	7	3	4	8	2	4	2	2	2	3	5
Ba	53	41	44	155	61	128	184	78	116	47	36	77	50
Rb	204	229	242	276	143	234	207	212	235	321	218	248	210
Sr	109	70	90	153	200	259	117	36	96	116	42	117	197
Zr	403	389	269	381	435	314	407	307	356	212	266	436	371
Y	51	46	68	60	49	41	49	65	59	61	66	51	49
Nb	240.1	216.5	312.6	357.8	238.2	198.7	245.3	305.6	387.4	214.2	452.0	214.8	201.8
Ga	28	28	26	30	27	23	28	34	32	24	33	27	24
Cu	21	14	16	16	11	16	15	18	16	18	15	21	16
Zn	99	118	211	174	99	97	134	148	160	242	114	110	209
Pb	8	18	133	7	5	7	19	3	14	116	5	22	161
La	108	99	21	49	114	83	113	23	36	19	22	102	87
Ce	205	191	51	97	220	162	212	55	76	48	56	200	175
Th	33	31	40	40	31	27	31	38	42	35	46	31	27
Nd	62	59	21	34	68	50	66	20	28	18	23	65	54
U	4	17	36	10	4	6	5	5	18	10	23	9	18
Cs	3	2	0	0	0	0	2	0	0	3	1	3	1
ICP-MS Trace Elements (ppm):													
La	105.31	99.43	21.44	49.37	115.53	84.66	113.93	22.94	37.16	21.15	23.68	107.31	94.29
Ce	201.81	187.29	50.88	97.75	219.60	161.59	215.74	53.55	78.26	49.70	57.54	204.10	177.60
Pr	20.57	19.19	6.07	10.87	22.48	16.58	22.16	6.09	8.72	5.78	7.00	21.00	18.31
Nd	63.41	59.12	20.15	34.72	69.45	50.59	68.25	19.22	27.13	18.55	23.79	64.03	56.15
Sm	11.55	10.62	6.52	8.38	12.48	9.32	12.11	5.37	7.18	5.74	8.11	11.45	10.50
Eu	1.18	1.07	0.43	0.86	1.32	0.97	1.22	0.35	0.61	0.38	0.53	1.18	1.12
Gd	8.87	8.25	7.27	7.64	9.47	7.14	9.05	5.70	6.91	6.17	8.75	8.75	8.44
Tb	1.53	1.34	1.60	1.57	1.54	1.24	1.50	1.40	1.50	1.44	1.81	1.50	1.50
Dy	9.10	7.90	10.72	10.25	9.00	7.52	8.98	10.16	9.91	9.80	11.40	9.20	9.05
Ho	1.76	1.56	2.09	2.02	1.73	1.45	1.72	2.12	2.00	1.95	2.21	1.81	1.74
Er	4.75	4.36	5.70	5.43	4.64	3.98	4.76	6.11	5.51	5.40	5.92	5.07	4.60
Tm	0.72	0.67	0.85	0.83	0.71	0.62	0.70	0.93	0.86	0.83	0.89	0.76	0.69
Yb	4.54	4.27	5.35	5.17	4.56	3.93	4.51	5.87	5.40	5.06	5.58	4.91	4.40
Lu	0.70	0.67	0.77	0.76	0.71	0.61	0.69	0.84	0.79	0.73	0.80	0.76	0.66
Ba	51	40	45	155	60	127	187	81	116	45	38	74	50
Th	29.44	30.41	38.88	38.89	30.46	26.13	29.84	37.75	41.61	34.00	45.18	30.11	27.52
Nb	238.0	209.0	310.2	354.6	224.2	184.2	238.5	305.8	388.4	213.7	445.9	211.4	198.9
Y	48.36	43.99	65.01	56.85	46.46	39.87	46.03	62.05	56.46	59.72	61.27	48.20	48.55
Hf	12.53	12.40	12.50	13.77	13.50	9.64	12.73	14.45	14.36	9.19	11.78	14.28	12.06
Ta	15.46	14.72	27.47	25.45	14.84	12.48	15.68	27.70	27.40	20.74	30.29	16.41	13.62
U	4.98	15.32	32.63	9.37	4.64	6.46	5.67	5.81	16.75	9.06	21.47	8.42	15.85
Pb	7.19	16.64	132.33	7.84	5.32	8.68	14.98	4.59	14.66	104.56	5.73	24.08	162.62
Rb	200.3	222.0	235.4	268.8	138.4	221.5	198.3	209.1	230.4	309.7	208.5	233.5	198.0
Cs	0.42	0.42	0.76	0.33	0.31	0.60	0.44	0.48	0.34	0.68	0.31	0.43	0.60
Sr	106	70	88	148	195	251	114	36	93	116	42	113	193
Sc	2.5	2.2	0.9	1.5	2.6	2.3	2.2	0.8	1.2	1.0	0.6	2.0	2.7
Zr	417	398	273	392	440	313	413	317	364	218	271	438	372
Isotope Ratios													
⁸⁷ Sr/ ⁸⁶ Sr _i	0.709658					0.708904			0.708549				
¹⁴³ Nd/ ¹⁴⁴ Nd _i	0.512639					0.512663			0.512667				

Table 2. U-Pb zircon analyses of the Cannon Point syenite (upper sill).

Spot	U (ppm)	²⁰⁶ Pb/ ²⁰⁴ Pb	U/Th	²⁰⁶ Pb*/ ²⁰⁷ Pb*	± (%)	²⁰⁷ Pb*/ ²³⁵ U	± (%)	²⁰⁶ Pb*/ ²³⁸ U	± (%)	Error Corr.	²⁰⁶ Pb*/ ²³⁸ U*	± (Ma)	²⁰⁷ Pb*/ ²³⁵ U*	± (Ma)	²⁰⁶ Pb*/ ²⁰⁷ Pb*	± (Ma)	Best Age (Ma)	± (Ma)
13	26	3298	0.8	21.5331	6.9	0.1282	7.2	0.0200	2.2	0.30	127.8	2.7	122.5	8.3	20.5	165.6	127.8	2.7
24	29	4920	0.6	20.5920	5.3	0.1344	6.0	0.0201	2.8	0.47	128.1	3.6	128.0	7.2	126.8	124.9	128.1	3.6
21	22	1908	0.6	25.1244	6.9	0.1103	7.5	0.0201	3.0	0.40	128.3	3.8	106.3	7.6	363.8	178.9	128.3	3.8
30	25	3383	0.8	23.5867	7.4	0.1180	7.9	0.0202	2.6	0.33	128.8	3.3	113.3	8.4	202.9	186.5	128.8	3.3
10	43	31195	0.5	21.0623	6.0	0.1326	6.4	0.0203	2.3	0.36	129.2	3.0	126.4	7.6	73.4	141.9	129.2	3.0
23	20	1303	0.8	23.5262	8.4	0.1188	9.1	0.0203	3.4	0.38	129.4	4.4	114.0	9.8	196.4	211.0	129.4	4.4
17	29	5396	0.6	22.0789	7.4	0.1267	7.7	0.0203	2.2	0.28	129.5	2.8	121.1	8.8	39.9	178.8	129.5	2.8
18	29	2319	0.7	21.7402	6.7	0.1288	7.3	0.0203	2.9	0.39	129.6	3.7	123.0	8.4	2.5	161.6	129.6	3.7
25	20	3788	0.8	21.1757	7.3	0.1325	8.0	0.0203	3.3	0.41	129.8	4.2	126.3	9.5	60.6	174.3	129.8	4.2
5	24	16916	0.7	18.9864	7.0	0.1484	7.5	0.0204	2.7	0.36	130.4	3.4	140.5	9.8	314.6	159.2	130.4	3.4
14	31	6736	0.6	19.0394	5.9	0.1480	6.3	0.0204	2.1	0.33	130.4	2.7	140.2	8.2	308.2	134.9	130.4	2.7
32	30	9326	0.6	19.1641	7.4	0.1471	8.1	0.0204	3.4	0.41	130.5	4.3	139.3	10.6	293.4	169.4	130.5	4.3
11	19	2214	0.8	20.5090	7.8	0.1376	8.1	0.0205	2.3	0.29	130.6	3.0	130.9	9.9	136.2	182.4	130.6	3.0
2	29	3169	0.6	25.7542	6.9	0.1096	7.2	0.0205	2.1	0.30	130.7	2.7	105.6	7.2	428.3	180.3	130.7	2.7
33	22	2553	0.6	21.6023	7.0	0.1308	7.5	0.0205	2.6	0.35	130.7	3.4	124.8	8.8	12.8	168.2	130.7	3.4
31	24	3830	0.8	20.7835	8.1	0.1361	8.6	0.0205	2.9	0.33	130.9	3.7	129.5	10.5	104.9	192.4	130.9	3.7
19	19	1665	0.8	23.1735	9.0	0.1225	9.8	0.0206	3.9	0.40	131.3	5.0	117.3	10.8	158.8	223.7	131.3	5.0
26	23	50756	0.7	21.5654	6.8	0.1316	7.4	0.0206	2.9	0.39	131.4	3.7	125.6	8.7	16.9	163.2	131.4	3.7
27	20	3484	0.8	19.4769	8.8	0.1461	9.5	0.0206	3.4	0.36	131.7	4.4	138.5	12.3	256.2	203.4	131.7	4.4
22	27	3927	1.0	23.9905	6.2	0.1190	7.0	0.0207	3.1	0.44	132.2	4.0	114.2	7.5	245.6	158.0	132.2	4.0
9	20	6093	0.8	19.3636	9.2	0.1478	9.6	0.0207	2.8	0.30	132.4	3.7	139.9	12.6	269.6	210.6	132.4	3.7
29	114	38544	0.6	20.6536	3.9	0.1387	4.3	0.0208	1.8	0.43	132.6	2.4	131.9	5.3	119.7	92.0	132.6	2.4
12	23	4383	0.6	19.3791	8.3	0.1479	8.7	0.0208	2.6	0.30	132.6	3.4	140.0	11.4	267.8	191.2	132.6	3.4
7	49	11726	0.5	22.9095	4.9	0.1251	5.3	0.0208	2.0	0.38	132.6	2.7	119.7	6.0	130.4	120.9	132.6	2.7
16	28	4424	0.6	19.1613	7.5	0.1499	7.9	0.0208	2.4	0.30	132.9	3.1	141.8	10.5	293.7	172.6	132.9	3.1
1	27	8558	0.7	21.6582	6.4	0.1329	6.9	0.0209	2.5	0.37	133.2	3.4	126.7	8.2	6.6	154.8	133.2	3.4
20	30	5994	0.8	12.1654	13.0	0.2369	13.2	0.0209	2.3	0.18	133.4	3.1	215.9	25.7	1250.3	255.1	133.4	3.1
15	20	15204	0.8	22.3856	6.8	0.1296	7.5	0.0210	3.3	0.44	134.2	4.3	123.7	8.8	73.5	165.5	134.2	4.3
4	23	6615	0.8	21.1002	6.8	0.1398	7.2	0.0214	2.5	0.34	136.4	3.3	132.8	9.0	69.1	161.7	136.4	3.3

Notes:

1. Analyses with >10% uncertainty (1-sigma) in $^{206}\text{Pb}/^{238}\text{U}$ age are not included.
2. Analyses with >10% uncertainty (1-sigma) in $^{206}\text{Pb}/^{207}\text{Pb}$ age are not included, unless $^{206}\text{Pb}/^{238}\text{U}$ age is <500 Ma.
3. Best age is determined from $^{206}\text{Pb}/^{238}\text{U}$ age for analyses with $^{206}\text{Pb}/^{238}\text{U}$ age <1000 Ma and from $^{206}\text{Pb}/^{207}\text{Pb}$ age for analyses with $^{206}\text{Pb}/^{238}\text{U}$ age > 1000 Ma.
4. Concordance is based on $^{206}\text{Pb}/^{238}\text{U}$ age / $^{206}\text{Pb}/^{207}\text{Pb}$ age. Value is not reported for $^{206}\text{Pb}/^{238}\text{U}$ ages <500 Ma because of large uncertainty in $^{206}\text{Pb}/^{207}\text{Pb}$ age.
5. Analyses with $^{206}\text{Pb}/^{238}\text{U}$ age > 500 Ma and with >20% discordance (<80% concordance) are not included.
6. Analyses with $^{206}\text{Pb}/^{238}\text{U}$ age > 500 Ma and with >5% reverse discordance (<105% concordance) are not included.
7. All uncertainties are reported at the 1-sigma level, and include only measurement errors.
8. Systematic errors are as follows (at 2-sigma level): [sample 1: 2.5% ($^{206}\text{Pb}/^{238}\text{U}$) & 1.4% ($^{206}\text{Pb}/^{207}\text{Pb}$)]. These values are reported on cells U1 and W1 of NUagecalc.
9. Analyses conducted by LA-MC-ICPMS, as described by Gehrels et al. (2008).
10. U concentration and U/Th are calibrated relative to Sri Lanka zircon standard and are accurate to ~20%.
11. Common Pb correction is from measured ^{204}Pb with common Pb composition interpreted from Stacey and Kramers (1975).
12. Common Pb composition assigned uncertainties of 1.5 for $^{206}\text{Pb}/^{204}\text{Pb}$, 0.3 for $^{207}\text{Pb}/^{204}\text{Pb}$, and 2.0 for $^{208}\text{Pb}/^{204}\text{Pb}$.
13. U/Pb and $^{206}\text{Pb}/^{207}\text{Pb}$ fractionation is calibrated relative to fragments of a large Sri Lanka zircon of 563.5 ± 3.2 Ma (2-sigma).
14. U decay constants and ratios used: $^{235}\text{U} = 9.8485 \times 10^{-10}$, $^{238}\text{U} = 1.55125 \times 10^{-10}$, $^{238}\text{U}/^{235}\text{U} = 137.88$.
15. Weighted mean plot created with Isoplot (Ludwig 2008).

Figure 3. Photomicrograph of sill margin showing sanidine phenocrysts with Carlsbad twinning set in a fine-grained, trachytic groundmass (sample CP-9A; XPL).

152x121mm (300 x 300 DPI)

<https://mc06.manuscriptcentral.com/cjes-pubs>

Figure 7. Weighted mean plot of concordant U-Pb zircon ages for the upper sill at Cannon Point.

111x94mm (300 x 300 DPI)

Figure 10. Initial Nd and Sr isotopic ratios of the Cannon Point sills compared to those of other Mesozoic granitoid intrusions from the WMMS (Foland and Allen 1991) and the Monterey Hills (Landoll and Foland 1996). Epsilon Sr and Nd values are relative to present day bulk Earth values.

123x107mm (300 x 300 DPI)

Figure 11. Trace element tectonic discrimination diagram for granitoid rocks (after Pearce et al. (1984)).
Monteregian Hills data from Landoll and Foland (1996); WMMS data from Eby et al. (1992).